

**SECTION 7—GUIDANCE, NAVIGATION, AND VEHICLE CONTROL
TECHNOLOGY**

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OVERVIEW

This section encompasses technologies for both autonomous and cooperative positioning, coordination, and control of military force elements, as noted in the military S&T Plans. Included are technologies for flight management, guidance, and vehicle control. Elements of the technology continue to be improved and adapted to mission needs. This is especially true for the U.S. Global Positioning System (GPS). Navigation is defined as obtaining the present condition or state of the vehicle from sensed values of position and motion. Guidance systems integrate these conditions and produce vehicle control responses. In essence, these technologies are closely coupled and overlap depending on application, which includes WMD. Most of these technologies have dual-use requirements, and all of them are essential for various mission needs. Commercial aircraft accuracy requirements are generally less than those for military aircraft. The trend is for consolidation of various navigation technologies into hybrid systems.

SECTION 7.1—AIRCRAFT AND VEHICLE CONTROL SYSTEMS

OVERVIEW

Flight control systems (FCS) (including Fly-by-Wire and Fly-by-Light) are composed of sensors, computers, actuators, and the other system components dictated by the architecture, methodologies, and algorithms required by the air vehicle (aircraft, RPV, or cruise missile) to perform its intended missions. Similar control systems are used in ground, sea, and space vehicle missions. They function to control the vehicle, including agility and steering, to achieve the desired flight path (e.g., weapon launch windows). The FCS also prevents undesirable aircraft and missile motions or structural loads by autonomously processing outputs from multiple sensors and then providing necessary preventive commands to effect automatic control. Flight path optimization is an FCS procedure that minimizes deviations from a four-dimensional (space and time) desired trajectory based on maximizing performance or effectiveness for mission tasks. Particularly important are evolving adaptive control techniques for integrated control and signature control. Control actuators transform control logic into vehicle responses. New technologies are required to further reduce power and logistic support. Electric actuators are used in small civil aircraft, RPVs, and missiles. They replace conventional hydraulic, pneumatic, and mechanical drive systems in larger, high-performance civil and military aircraft and helicopters.

Table 7.1-1. Aircraft and Vehicle Control Systems Militarily Critical Technology Parameters

| TECHNOLOGY | Militarily Critical Parameters Minimum Level to Assure US Superiority | Critical Materials | Unique Test, Production, and Inspection Equipment | Unique Software and Parameters | Control Regimes |
|--|--|-----------------------------------|--|--|-------------------------|
| AIRFOILS, VARIABLE GEOMETRY | Fixed wing - external robustness to maximize L/D configured airfoil from supersonic only to include high subsonic region. Helicopter - Dynamically optimized airload distribution on rotors for 50% reduction in acoustic signature and 60% less vibration; Bandwidth of > 3 Hz | Smart materials | Digital air vehicle and control system dynamic computer models; CAD development software; pilot in-the-loop simulators; ground and flight testing of prototype systems; CAD tools for linking design parameters to vehicle dynamic models. | Algorithms and verified data containing actual design parameters (e.g., response, shape, rates). | WA ML 10 WA IL Cat 7 |
| CONTROLLER, MULTI-AXIS | Cooper-Harper rating of < 3; No pilot induced oscillation (PIO) due to rate limiting | None identified | Digital air vehicle and control system dynamic computer models; CAD development software; pilot in-the-loop simulators; ground and flight testing of prototype systems. | Algorithms and verified data containing actual design parameters (e.g., gains, time constants, limits, thresholds). | WA ML 10 WA IL Cat 7 |
| ELECTRIC ACTUATORS | Output power > 4 hp; Rate > 50 deg/s; Acceleration > 100 inches/sec ² ; Bandwidth > 4 Hz | Rare earth magnets; see Materials | Digital air vehicle and control system dynamic computer models; pilot in-the-loop simulators; ground and flight testing of prototype systems; CAD tools for developing power controllers. | Algorithms and verified data containing actual design parameters (e.g., power switching logic, gains, time constants). | WA ML 10 WA IL Cat 7 |

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Table 7.1-1. Aircraft and Vehicle Control Systems Militarily Critical Technology Parameters (Continued)

| TECHNOLOGY | Militarily Critical Parameters Minimum Level to Assure US Superiority | Critical Materials | Unique Test, Production, and Inspection Equipment | Unique Software and Parameters | Control Regimes |
|--|--|--------------------|---|--|-------------------------|
| FLIGHT CONTROL SYSTEMS, ACTIVE | 30% reduction in pilot fatigue in 1-2 Hz region caused by turbulence induced structural oscillations; minimize flutter for aeroelasticity induced airspeed limits; 50% increase in structural fatigue life. | None identified | Air vehicle rigid, flexible and control system dynamic computer models; CAD development software; pilot in- the-loop simulators; ground and flight testing of prototype systems; CAD tools for linking design parameters with flexible vehicle dynamics. | Algorithms and verified data containing actual design parameters (e.g., gains, time constants, limits) for military applications. Automatic verification and validation tools. | WA ML 10 WA IL Cat 7 |
| FLIGHT CONTROL SYSTEMS, FULL AUTHORITY DIGITAL | Equivalent time delay of < 100 milliseconds; bandwidth of > 3 Hz; Aircraft loss rate per flight of < 1×10^{-5} | None identified | Digital air vehicle and control system dynamic computer models; CAD development software; pilot in- the-loop simulators; ground and flight testing of prototype systems. | Algorithms and verified data containing actual design parameters (e.g., gains, time constants, limits). Automatic verification and validation tools. | WA ML 10 WA IL Cat 7 |
| FLIGHT CONTROL SYSTEMS, MULTI- DISCIPLINED INTEGRATED | Equivalent time delay of < 100 milliseconds; Bandwidth of > 3 Hz; Time to identify structural modes < time to double amplitude | None identified | Integrated air vehicle control system, structural and propulsion dynamic computer models; pilot in-the- loop simulators; ground and flight testing of prototype systems; CAD tools for linking individual disciplinary models. | Algorithms and verified data containing actual design parameters (e.g., gains, time constants, limits). Automatic verification and validation tools. | WA ML 10 WA IL Cat 7 |
| FLIGHT CONTROL SYSTEMS, RECONFIGURABLE | Detect and respond in less than the time to reach double amplitude | None identified | Digital air vehicle and control system dynamic computer models; pilot in-the- loop simulators; ground and flight testing of prototype systems; CAD tools for linking individual disciplinary models. | Algorithms and verified data containing actual design parameters (e.g., gains, time constants, limits). Automatic verification and validation tools. | WA ML 10 WA IL Cat 7 |

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Table 7.1-1. Aircraft and Vehicle Control Systems Militarily Critical Technology Parameters (Continued)

| TECHNOLOGY | Militarily Critical Parameters Minimum Level to Assure US Superiority | Critical Materials | Unique Test, Production, and Inspection Equipment | Unique Software and Parameters | Control Regimes |
|--|--|--------------------|--|--|-------------------------|
| FLIGHT CONTROL SYSTEMS, THRUST VECTURING | Equivalent time delay of < 100 milliseconds; Bandwidth of > 3 Hz; Rate limit > 60 deg/sec | None identified | Integrated air vehicle control system, structural and propulsion dynamic computer models; pilot in-the- loop simulators; ground and flight testing of prototype systems; CAD tools for linking propulsion and vehicle dynamic models. | Algorithms and verified data containing actual design parameters (e.g., gains, time constants, limits). Automatic verification and validation tools. | WA ML 10 WA IL Cat 7 |
| NONCONVENTIONAL (OPTICAL/MODELING) AIR DATA SENSORS | Operation > 30,000 ft Covert Air Data with accuracy equivalent to conventional sensors | None identified | Unique computer models and laser velocimetry CAD Development Tools for linking algorithms and aircraft shapes | Compensation algorithms and verified data. | WA ML 10 WA IL Cat 7 |

SECTION 7.2—INERTIAL NAVIGATION SYSTEMS AND RELATED COMPONENTS

OVERVIEW

This technology area encompasses a wide range of systems and components that form the basis for autonomous, covert navigation and motion sensing. Included are Inertial Navigation Systems (INS), various types integrated systems, and each of many distinct types of gyroscopes and accelerometers that can be found in a navigation system. Multifunction inertial components are also noted. An INS is a self-contained system that provides continuous estimates of some or all components of vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs. An INS contains accelerometers and gyroscopes to sense linear and angular rate. It can be mechanized either as a gimballed platform or a strapdown inertial sensing unit employing a computer to provide the "software" equivalent of gimbals or a hybrid unit with either gimbal or strapdown features. Gyros and accelerometers can also be used as separate instruments. Separate militarily critical technology areas and parametric controls apply to gyros, accelerometers, and systems. (See Figs. 7.2-1 and 7.2.2, which provide examples of applications.)

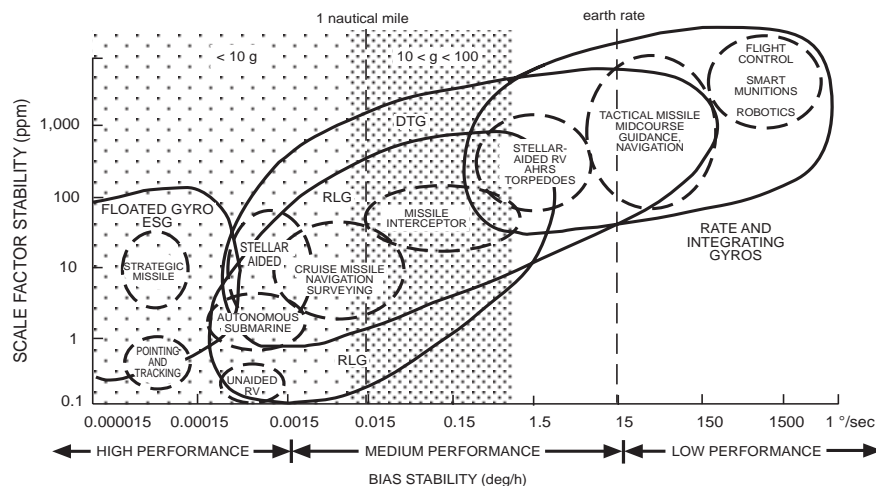


Figure 7.2-1. Gyro Technology Applications (shaded area is militarily critical region)

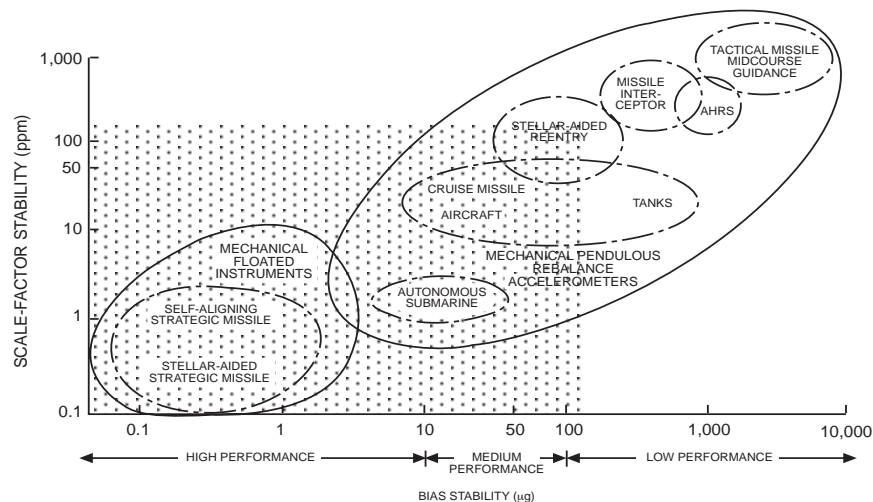


Figure 7.2-2. Accelerometer Technology Applications (shaded area is militarily critical region)

Table 7.2-1. Inertial Navigation Systems and Related Components Militarily Critical Technology Parameters

| TECHNOLOGY | Militarily Critical Parameters Minimum Level to Assure US Superiority | Critical Materials | Unique Test, Production, and Inspection Equipment | Unique Software and Parameters | Control Regimes |
|---|--|-----------------------|---|--|-----------------------------------|
| INERTIAL NAVIGATION SYSTEMS | For Aircraft, Vehicle or Spacecraft for attitude, guidance and control - Nav error < 0.8 nmi/hr 50% CEP For ships - Nav error of < 0.8 nmi in 3 hrs For missiles - Nav error of < 2 nmi/hr Or specified to function at linear acceleration > 10 g on any platform | None identified | Components require specially designed test, calibration, or alignment equipment Ships motion simulator CAD development tools for linking various design parameters | Algorithms and verified data needed to exceed militarily critical parameters. INS alignment time for moving platform and transfer alignment techniques | WA ML 9 MTCR WA IL Cat 7 |
| HYBRID NAVIGATION SYSTEMS | For A/C, Vehicle or Spacecraft - Nav error < 0.8 nm/hr 50% CEP For ships - Nav error of < 0.8 nmi in 3 hrs For missiles - Nav error of < 2 nmi/h Or specified to function at linear Acceleration > 10 g on any platform | None identified | Components require specially designed test, calibration, or alignment equipment. GNSS receivers require special simulator testing systems. CAD development tools for linking various design parameters | Algorithms and verified data needed to exceed militarily critical parameters. Source code for combining INS with Doppler, GNSS or DBRN. INS initial align time for moving platform. Transfer align techniques and reference to geoid | WA ML 9 MTCR WA IL Cat 7 |
| INERTIAL/GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS) | For A/C, Vehicle or Spacecraft - Nav error < 0.8 nm/hr 50% CEP Pointing accuracy < 75 arc sec For ships - Nav error of < 0.8 nmi in 3 hrs For missiles - Nav error of < 2 nmi/hr Or specified to function at linear acceleration > 10 g on any platform Signal decryption (anti spoof) and/or null-steerable antenna, jamming protection. Accuracy of < 20 meter 50% SEP in position and < 200 nanosecond in time. < 0.1 m/s velocity > 60,000 ft and > 1,000 kts | None identified | Components require specially designed test, calibration, or alignment equipment. GNSS receivers require special simulator testing systems. CAD development tools for linking various design parameters | Algorithms and verified data needed to exceed militarily critical parameters. Source code for combining INS with GNSS. INS initial align time for moving platform. Transfer align techniques and reference to geoid | WA ML 9 MTCR WA IL Cat 7 |
| GYRO ASTRO TRACKING DEVICES | Azimuth accuracy < 75 arc seconds Or specified to function at linear acceleration >10 g on any platform | None identified | Components require specially designed test, calibration, or alignment equipment including clock accuracy of 1 micro- second/24 hrs Star signal simulators CAD development tools for linking various design parameters | Algorithms and verified data needed to exceed militarily critical parameters. Source code for combining with INS. Transfer align techniques and reference to geoid | WA ML 9 MTCR WA IL Cat 7 |

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Table 7.2-1. Inertial Navigation Systems and Related Components Militarily Critical Technology Parameters (Continued)

| TECHNOLOGY | Militarily Critical Parameters Minimum Level to Assure US Superiority | Critical Materials | Unique Test, Production, and Inspection Equipment | Unique Software and Parameters | Control Regimes |
|---|--|-----------------------|---|---|--------------------------------|
| GYROSCOPES | Drift rate stability of < 0.01 deg/hr for < 10 g or Drift rate stability of < 0.5 deg/hr for 10 to 100 g or specified to function at linear acceleration levels > 100 g on any platform See Figure 7.2-1 | None identified | Gyro tuning test and dynamic balance station Gyro run-in motor test station Evacuation and fill stations Centrifuge fixtures for gyro bearings Scatterometers-accuracy > 10 ppm Profilometers-accuracy < 5 angstrom Fiber winding machines CAD development tools for linking various design parameters | Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics | WA ML 9 MTCR WA IL Cat 7 |
| ACCELEROMETERS | Bias stability of < 130 micro g or Scale factor stability of < 130 ppm or Specified to function at linear acceleration levels > 100 g on any platform See Figure 7.2-2 | None identified | Specially designed test, calibration, or alignment equipment Accelerometer axis align stations Programmable dividing head CAD development tools for linking various design parameters | Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics | WA ML 9 MTCR WA IL Cat 7 |
| MULTI-FUNCTION INERTIAL COMPONENTS | Combination of gyro and accelerometer parameters with limiting tolerance parameter being a drift rate stability of < 0.01 deg/hr for < 10 g or Drift rate stability of < 0.5 deg/hr for 10 to 100 g or specified to function at linear acceleration levels > 100 g on any platform | None identified | Specially designed test, calibration, or alignment equipment Accelerometer axis align stations | Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics | WA ML 9 MTCR WA IL Cat 7 |
| AZIMUTH DETERMINATION SYSTEM | < 3 arc minutes Refer to parameters for gyroscopes | None identified | Components require specially designed test, calibration, or alignment equipment | Algorithms and verified data needed for compensation | WA ML 9 WA IL Cat 7 |
| FLOATED GYROSCOPES | Drift rate stability of < 0.01 deg/hr for < 10 g or Drift rate stability of < 0.5 deg/hr for 10 to 100 g or Specified to function at acceleration levels > 100 g on any platform | None identified | Gyro dynamic balance station Gyro run-in motor test station Gyro evacuation and fill stations Centrifuge fixtures for gyro bearings | Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics | WA ML 9 MTCR WA IL Cat 7 |

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Table 7.2-1. Inertial Navigation Systems and Related Components Militarily Critical Technology Parameters (Continued)

| TECHNOLOGY | Militarily Critical Parameters Minimum Level to Assure US Superiority | Critical Materials | Unique Test, Production, and Inspection Equipment | Unique Software and Parameters | Control Regimes |
|---|--|-----------------------|--|---|-----------------------------------|
| DYNAMICALLY TUNED GYROSCOPES (DTG) | Drift rate stability of < 0.01 deg/hr for < 10 g or Drift rate stability of < 0.5 deg/hr for 10 to 100 g or Specified to function at acceleration levels > 100 g on any platform | None identified | Gyro tuning test station Gyro dynamic balance station Gyro run-in motor test station Gyro evacuation and fill stations Centrifuge fixtures for gyro bearings | Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics | WA ML 9 MTCR WA IL Cat 7 |
| RING LASER GYROSCOPES (RLG) | Drift rate stability of < 0.01 deg/hr for < 10 g or Drift rate stability of < 0.5 deg/hr for 10 to 100 g or Specified to function at acceleration levels > 100 g on any platform | None identified | Scatterometers- accuracy < 10 ppm to characterize mirrors Profilometers- accuracy < 5 angstrom to characterize mirrors Gyro evacuation and fill stations Ion beam coating facilities Electron beam evaporation machines CAD development tools for linking various design parameters | Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics | WA ML 9 MTCR WA IL Cat 7 |
| ELECTRO- STATICALLY SUPPORTED GYROSCOPES (ESG) | Drift rate stability of < 0.01 deg/hr for < 10 g or Drift rate stability of < 0.5 deg/hr for 10 to 100 g or Specified to function at acceleration levels > 100 g on any platform | None identified | Gyro evacuation and fill stations CAD development tools for linking various design parameters | Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics | WA ML 9 MTCR WA IL Cat 7 |
| FIBER OPTIC GYROSCOPES (FOG) | Drift rate stability of < 0.01 deg/hr for < 10 g or Drift rate stability of < 0.5 deg/hr for 10 to 100 g or Specified to function at acceleration levels > 100 g on any platform | None identified | Fiber winding machines CAD development tools for linking various design parameters | Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics | WA ML 9 MTCR WA IL Cat 7 |
| HEMISPHERICAL RESONATOR GYROSCOPES (HRG) | Drift rate stability of < 0.01 deg/hr for < 10 g or Drift rate stability of < 0.5 deg/hr for 10 to 100 g or Specified to function at acceleration levels > 100 g on any platform | None identified | Gyro dynamic balance station Gyro evacuation and fill stations Surface etching techniques | Algorithms and verified data needed to exceed militarily critical parameters. Unique compensation techniques | WA ML 9 MTCR WA IL Cat 7 |

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Table 7.2-1. Inertial Navigation Systems and Related Components Militarily Critical Technology Parameters (Continued)

| TECHNOLOGY | Militarily Critical Parameters Minimum Level to Assure US Superiority | Critical Materials | Unique Test, Production, and Inspection Equipment | Unique Software and Parameters | Control Regimes |
|--|--|-----------------------|--|---|-----------------------------------|
| MICRO ELECTRO- MECHANICAL (SILICON) GYROS | Drift rate stability of < 0.01 deg/hr for < 10 g or Drift rate stability of < 0.5 deg/hr for 10 to 100 g or Specified to function at acceleration levels > 100 g on any platform | None identified | Specially designed test, calibration, or alignment equipment Accelerometer axis align stations Ion milling Plasma Arc Electronic Sputtering | Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics | WA ML 9 MTCR WA IL Cat 7 |
| MICRO ELECTRO- MECHANICAL (SILICON) ACCELEROMET ERS | Bias stability of < 130 micro g or Scale factor stability of < 130 ppm or Specified to function at acceleration levels > 100 g on any platform | None identified | Specially designed test, calibration, or alignment equipment Accelerometer axis align stations Ion milling Plasma Arc Electronic Sputtering | Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics | WA ML 9 MTCR WA IL Cat 7 |

SECTION 7.3—RADIO AND DATA-BASED REFERENCED NAVIGATION SYSTEMS

OVERVIEW

This subsection covers a limited category of technology and equipment having a wide range of dual-use applications. GNSS receivers with certain characteristics have proliferation concerns, especially when used in the differential and hybrid modes using compensating systems for improving accuracy and redundancy. Accurate time and frequency form the baseline for telecommunications and navigation. DBRN provides highly accurate position, velocity, and track under dynamic and **covert** conditions. DBRN systems use **prestored** ground and undersea terrain contour, acoustic, electromagnetic spectrum, magnetic, gravity, and stellar sensor data. Radio navigation equipment using low probability of intercept techniques also provides covert capability.

Table 7.3-1. Radio and Data-Based Referenced Navigation Systems Militarily Critical Technology Parameters

| TECHNOLOGY | Militarily Critical Parameters Minimum Level to Assure US Superiority | Critical Materials | Unique Test, Production, and Inspection Equipment | Unique Software and Parameters | Control Regimes |
|--|---|-----------------------|--|---|-------------------------------------|
| GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS) | Signal decryption (anti spoof) and/or null-steerable antenna, jamming protection Accuracy of < 20 meter 50% SEP in position and < 200 nanosecond in time and < 0.1 m/s velocity for > 60,000 ft and > 1,000 kts | None identified | Selective Availability, Anti- Spoofing (SA/A-S) Signal Simulators with SA/A-S < 200 nanosecond measurement capability ECCM or Interference Resistance Receivers | Algorithms including classified, encrypted algorithms and verified data. Vehicle attitude determination | MTCR 1 WA ML 9 WA IL Cat 7 |
| DIFFERENTIAL GNSS | Signal decryption (anti spoof) and/or null-steerable antenna, jamming protection Accuracy of < 1 meter 50% SEP in position and < 200 nanosecond in time and < 0.1 m/s velocity for > 60,000 ft and > 1,000 kts | None identified | Selective Availability, Anti- Spoofing (SA/A-S) Signal Simulators with SA/A-S < 200 nanosecond measurement capability | Algorithms including classified, encrypted algorithms and verified data. Differential techniques that provide accuracy of < 1 meter. Vehicle attitude determination | MTCR 1 WA ML 9 WA IL Cat 7 |
| HYBRID NAVIGATION SYSTEMS | Accuracy of < 20 meter 50% SEP in position. Jamming protection to maintain PPS or < 0.1 m/s velocity for > 60,000 ft and > 1,000 kts For spacecraft - Pointing accuracy of < 50 arc sec | None identified | Components require specially designed test, calibration, or alignment equipment. GNSS receivers require special simulator testing systems. Specially designed test, calibration, or alignment equipment | Algorithms and verified data needed to exceed militarily critical parameters. Source code for combining INS with Doppler, GNSS or DBRN. INS initial align time code for moving platform, transfer align techniques and reference to geoid | MTCR 1 WA ML 9 WA IL Cat 7 |

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Table 7.3-1. Radio and Data-Based Referenced Navigation Systems Militarily Critical Technology Parameters (Continued)

| TECHNOLOGY | Militarily Critical Parameters Minimum Level to Assure US Superiority | Critical Materials | Unique Test, Production, and Inspection Equipment | Unique Software and Parameters | Control Regimes |
|--|---|---|---|---|--------------------------------------|
| PRECISION TIME AND FREQUENCY SUBSYSTEMS | Signal phase (time) communication synchronization < 100 microseconds, UTC (USNO). Intersystem synchronization < 100 nanoseconds relative to other system nodes. Navigation systems < 200 nanoseconds, UTC (USNO). Frequency for reference and calibration, $\Delta f / f < 1 \times 10^{-10}$. | Synthetic quartz Magnetic shielding materials, see Materials | Frequency for reference and calibration, $\Delta f / f < 1 \times 10^{-10}$ | Algorithms and verified data needed to combine clock outputs to improve stability/accuracy performance (i.e., "Ensembling") Automatically detect phase jumps or frequency pertur- bations and/or improve reliability from redundancy. Self monitoring. | WA IL Cat 3 MTCR |
| RADAR ALTIMETERS AND DOPPLER NAVIGATION SYSTEMS HAVING POWER MANAGEMENT OR PHASE SHIFT KEY MODULATION | Non detectable – in radar frequency range | None identified | None identified | Cross correlation algorithms and verified data. | MTCR 11 WA ML 9 WA IL Cat 7 |
| DATA BASED (FOR EXAMPLE TERRAIN, ACOUSTIC, ELECTRO- MAGNETIC SPECTRUM, MAGNETIC, GRAVITY, GRAVITY GRADIENT, BATHYMETRIC, STELLAR) REFERENCED NAVIGATION | Accuracy < 100 meters CEP | None identified | Unique computer test models for optimization of data base manipulation and extraction | Algorithms for image correlation and pattern recognition. Integration and data analysis algorithms and verified data | MTCR 11 WA ML 9 WA IL Cat 7 |